Gait & Posture 67 (2019) 104–111

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Full length article

Kinematic adaptation and changes in gait classification in running compared to walking in children with unilateral spastic cerebral palsy

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ARTICLE INFO

Keywords:
Unilateral spastic cerebral palsy
Gait classification
Running
Gait analysis

ABSTRACT

Background: Classification of sagittal gait patterns in unilateral spastic cerebral palsy (CP) provides direct implication for treatment. Five types are described: type 0 has minor gait deviation; type 1 has inadequate ankle dorsiflexion in swing; type 2 has inadequate ankle dorsiflexion throughout the gait cycle; types 3 and 4 have abnormal function of the knee and hip joint respectively. During gait analysis of children with unilateral spastic CP we observed frequently that a knee flexion deficit disappeared during running. That may have an impact on classification and treatment.

Research question: Does the classification type change while running and how do patients' kinematics adapt to running?

Methods: 64 children with unilateral spastic CP were classified using instrumented gait analysis for walking and running. The deviation of four parameters from typically developing children (TD) were used to distinguish between types: peak ankle dorsiflexion in swing for type 1, peak ankle dorsiflexion in stance for type 2, knee range of motion for type 3, and hip range of motion for type 4. A three-factor ANOVA for factors group (CP/TD), locomotion (walk/run) and limb side (in-/uninvolved) was conducted.

Results: The number of patients with type 1, 3 and 4 decreased considerably from walking to running, whereas, the number of type 0 and 2 patients increased. The ANOVA showed that three of four parameters of patients' pathologic limb adapt similarly to TD to running, except for the ankle dorsiflexion in stance.

Significance: Running shows that there is a natural way to resolve abnormalities. Therefore, recommended treatments of hip and knee joint abnormalities based on the walking classification can be questioned and additional running analysis may be important for surgical decision making.

1. Introduction

In patients with unilateral spastic cerebral palsy (USCP), four typical walking abnormalities have been classified [1–3]. This classification was shown to be relevant for the non-surgical and surgical treatment of the patients [1,2,4,5]. The classification is based on the ankle, the knee and the hip joint of the patient's affected limb. Abnormal motion and the resulting abnormal kinematic parameters in three-dimensional motion analysis characterize those pathologies. Winters et al. [1] visually classified the hemiplegic patients into these four groups with an increasing degree of involvement from group I to IV according to the following abnormalities. Group I has an inability for dorsiflexion in the ankle joint during the swing phase of the gait cycle, while still showing adequate dorsiflexion in stance. Drop foot is the only occurring abnormality [1–3]. The main problem seems to be a weakness or underactivity of the anterior tibial muscle in contrast to hyperactivity of the gastrocnemius and soleus muscle. Thus, the required treatment is a leaf spring ankle foot orthosis [1,4]. Group II patients show an equinus abnormality characterized by contracture and/or spasticity of the gastroc-soleus muscles resulting in an inadequate dorsiflexion in the stance and swing phase of gait with a persistently plantar flexed ankle joint [1–3,6]. The intramuscular injection of Botulinum Neurotoxin (BoNT) is a common spasticity treatment especially in younger children [4]. An ankle foot orthosis should provide orthotic support and surgical lengthening of the gastrocnemius and soleus or Achilles tendon may be performed [4]. Group III patients have an additional dysfunction of the

Abbreviations: BoNT, Botulinum Neurotoxin; CP, Cerebral palsy; USCP, Unilateral spastic cerebral palsy; TD, Typically developing; CPG, Central pattern generator; RoM, Range of motion; DF, Dorsiflexion; SD, Standard deviation

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https://doi.org/10.1016/j.gaitpost.2018.09.031
Received 11 September 2017; Received in revised form 6 September 2018; Accepted 28 September 2018

knee joint, such as crouch gait or stiff knee gait, as the result of hamstring/quadriceps co-contraction [1–3,4,6]. Spastic hamstring muscles can be treated with BoNT injections. Surgical contracture management consists of lengthening the medial hamstring muscles and transferring the rectus femoris muscle to the gracilis or semitendinosus [4]. Group IV patients have an additional dysfunction of the hip joint. BoNT injections in the medial hamstrings, hip adductors, and hip flexors as well as surgical lengthening of the hip adductors and iliopsoas are recommended [1–3,4]. Winters et al. [1] described a cumulative classification where a higher group show abnormalities of the lower groups, but USCP patients usually can show one or more of the abnormalities in different combinations [6]. If a patient is more neurologically involved, more proximal abnormalities occur [1]. A group 0 was added for patients who do not show obvious abnormalities but are still neurologically involved [2,3].

During gait analysis of USCP children in our institution, it was frequently observed that a stiff knee gait during walking analysis was dissolved during running (Fig.1A). It was shown that knee range of motion in running in diplegic CP patients did not exceed their walking values [7]. Thus, we wondered whether typical abnormal gait deviations can normalize with running in USCP children. If USCP patients show more normal patterns in running compared to walking, this could question recommended treatment strategies and would suggest including a running analysis for treatment planning. So the purposes of this study were to analyze if USCP patients change classification type from walking to running and to compare the adaptation of patients' kinematics during running to normal adaptation.

2. Methodology

2.1. Patients and controls

Patients with USCP between 4 and 17 years of age were retrospectively selected from the database of the Gait Analysis Laboratory from 2006 to 2016. All patients had been referred to the Gait Analysis Laboratory at our institution for evaluation of their gait and assessment for useful orthotic or orthopedic interventions. Besides gait analysis, physical examination was conducted for every patient. The children provided written consent, as approved by the local ethics committee. To be included, the children had to be community-level ambulators using no assistive devices (GMFCS I &II). Excluded were patients with other types of cerebral palsy such as ataxia, dystonia, or athetosis and patients that were not able to understand verbal instructions. If there were follow up measurements for the same patient in the database the measurement at the youngest age of the patient was analyzed.

All patients were asked to walk and run at comfortable self-selected speed. Further, when asked to run they should show a phase of double float where neither foot touches the ground [8]. Three consistent trials of walking and running for each limb were considered for evaluation. We determined consistency by visually checking the gait curves.

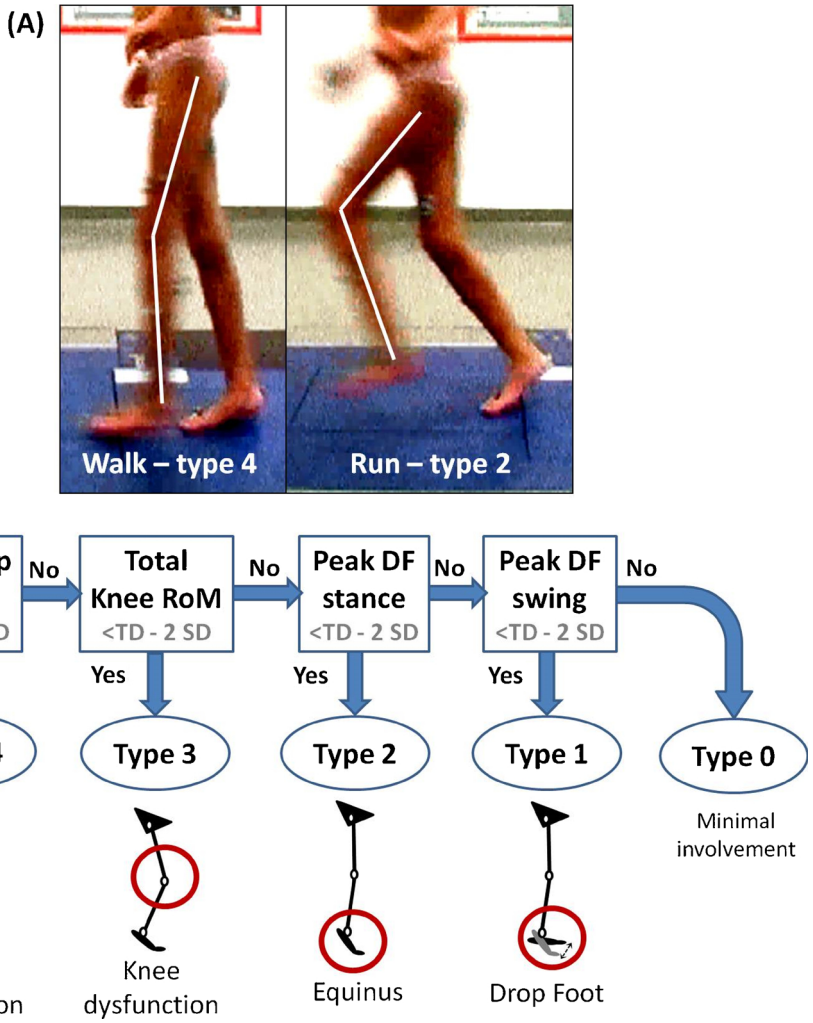

Fig. 1. A: Patient with knee flexion deficit in walking but not in running classified as walking type 4 and running type 2; B: Flow diagram of the extended classification algorithm based on McDowell et al. [3], starting with patients' Total Hip RoM compared to the mean of TD minus 2SD.

Patients' involved limb was considered for gait classification. Evaluation of their neurologic involved limb (pathologic side) and their uninvolved limb (contralateral side) were considered for inferential statistics. Finally, 64 USCP children were included. Their mean age was 9.5 years (SD = 3.0) with a mean bodyweight of 33.7 kg (SD = 12.4). Their mean body height was 138 cm (SD = 17.2), and their mean body mass index was 17 kg/m^2 (SD = 2.6). The USCP group consisted of 37 males and 27 females. Thirty-three patients had left side spastic hemiplegia and thirty-one had right side spastic hemiplegia.

The measurement of the 30 typically developing children (TD) served as a reference group. Regarding gait classification, one limb of each TD was randomly selected for calculating TD mean values. Both limbs were considered for inferential statistic evaluation and randomly assigned to either prime side (analogue to USCP pathologic side) or contralateral side. TDs' mean age was 9.7 years (SD = 2.7) with a mean bodyweight of 35.2 kg (SD = 12.7). Their mean body height was 143 cm (SD = 17.9), and their mean body mass index was 16.7 kg/m^2 (SD = 2.2). This reference group consisted of 15 males and 15 females.

2.2. Classification and evaluation

Instrumented gait analysis was performed using an eight-camera Vicon MX system (Vicon Inc., Oxford, UK) with two force plates (AMTI, Watertown, MA, USA). The walkway was 15 m in distance. The Vicon Plug-in-Gait marker set and model were used to generate kinematic data. The sagittal parameters of the lower limb total hip range of motion (hip RoM), total knee range of motion (knee RoM), peak dorsiflexion of the ankle in stance (ankle DF stance) and swing phase (ankle DF swing) were analyzed.

A configured classification algorithm, based on McDowell et al. [3], was executed for walking and running to automatically determine the different classification types of patients. The patients' pathologic limb values of hip RoM, knee RoM, ankle DF stance, and ankle DF swing were compared to the mean value minus two standard deviations (2SD) of the TD group for the respective parameters to classify every patient for walking and running. The classification algorithm starts with the hip RoM parameter. If patients' values were below the TD mean value minus 2SD this was considered evidence showing hip dysfunction (hip RoM), knee dysfunction (knee RoM), equinus (ankle DF stance) or drop foot (ankle DF swing) respectively. See Fig.1B for the flow diagram of the classification algorithm.

A three-way ANOVA for factors group (USCP/TD), locomotion (walk/run) and limb side (pathologic/contralateral) was conducted for evaluating group, locomotion and limb differences for hip/knee RoM and ankle DF stance/swing parameters. The p-value had to be less than or equal to 0.05 for all tests in order to be considered significant.

3. Results

USCP children had a mean non-dimensional walking velocity of 0.44 (SD = 0.06), and running velocity of 0.96 (SD = 0.18). Their non-dimensional step length increased from 72.2 (8.5) in walking to 104.0 (17.0) in running and their non-dimensional step time decreased from 1.83 (0.17) in walking to 1.15 (1.12) in running. TDs' non-dimensional velocity increased from 0.48 (0.05) in walking to 1.03 (0.21) in running. Their non-dimensional step length increased from 82.1 (6.8) in walking to 120.0 (19.2) in running and their non-dimensional step time decreased from 1.69 (0.10) in walking to 1.15 (0.10) in running. See Table 1 for further description of anthropometrical data, spatio-temporal parameters and physical examination data.

3.1. Number of gait types and pathologies

The number of patients with different classification types in walking and running are shown in Fig.2A and Fig.2B respectively. Types 4, 3 and 1 decreased and type 2 and type 0 increased in number from walking to running. All in all 44% (28/64) improved into a lower type, 40% (26/64) stayed equal in the same type and 16% (10/64) deteriorated into a higher type. Detailed type changes are shown in Fig.2C.

Regarding the gait abnormalities that are the basis of the classification we evaluated the following results (Fig.2D). In walking, 64% (41/64) of the patients showed drop foot abnormality, 38% (24/64) showed equinus abnormality, 44% (28/64) showed knee dysfunction abnormality, and 17% (11/64) showed hip dysfunction abnormality. In running 39% (25/64) patients showed drop foot abnormality, 59% (38/64) showed equinus abnormality, 9% (6/64) showed knee dysfunction abnormality, and 6% (4/64) showed hip dysfunction abnormality. The number of patients who showed drop foot, hip dysfunction and knee dysfunction abnormality decreased from walking to running, whereas, the number of patients who showed an equinus abnormality increased during running. This implies that 39% (16/41) with a drop foot in walking, 79% (22/28) with a knee dysfunction in walking, and 64% (7/11) with a hip dysfunction in walking normalized during running respective to those abnormalities. Moreover, 96% (23/24) with equinus abnormality in walking showed an equinus in running and 39% (15/38) with no equinus in walking showed an equinus in running.

3.2. ANOVA for group, locomotion and limb side

Means and SD of USCP and TD in walking and running of pathologic/prime and contralateral side for the four parameters ankle DF swing, ankle DF stance, knee RoM and hip RoM are shown in Fig.3. The p-values and effect sizes resulting from the ANOVA are summarized in Table 2.

We observed significant main effects for the group factor for ankle DF swing, ankle DF stance, and knee RoM, but not for hip RoM. The main effect for the locomotion factor was significant in all four parameter. The main effect for the limb side factor was significant for ankle DF swing, ankle DF stance, and hip RoM, but not for knee RoM.

The group × locomotion interaction effect was significant for ankle DF stance, knee RoM, and hip RoM. In ankle DF swing there was no significant group × locomotion interaction. The group × limb side interaction was highly significant for ankle DF swing, ankle DF stance and hip RoM with strong effect sizes. No significant group × limb side interaction was observed in the knee RoM. The locomotion × limb side interaction was significant for the ankle DF stance, knee RoM and hip RoM. Only the locomotion × limb side interaction for ankle DF swing was not significant. A significant group × locomotion × limb side interaction was observed in ankle DF stance and knee RoM. Both η^2-values showed a moderate effect size. For ankle DF swing and hip RoM it was not significant.

Fig.4 contains further information about sagittal kinematics of group (USCP, TD), locomotion (walk, run) and limb side (pathologic/prime, contralateral) throughout the gait cycle.

4. Discussion

The results indicate normalization of abnormalities from walking to running for hip and knee joint dysfunction and inadequate ankle dorsiflexion in swing. Therefore, we observed a decreasing number of patients classified as type 1, 3 and 4 from walking to running. Similarly to TD controls, the hip and knee joints' excursion as well as the dorsiflexion in swing of the patients' pathologic limb adapted from walking to running. Only the ankle dorsiflexion in stance phase (equinus abnormality) showed an inadequate adaptation different than the TD controls while running and thus the number of classification type 2′s increased from walking to running. The equinus abnormality seems to be the main problem in USCP children that remained during running analysis.

In the three-factor ANOVA the non-significant group × locomotion × limb side effect in hip RoM and ankle DF swing parameters showed that the adaptation from walking to running was similar to normal

Table 1
Mean (SD) values of age, anthropometrical data, non-dimensional velocity and step length/time (non-dim.) normalized according to Hof [18], passive joint excursion in degree [°] (popliteal angle through Thomas test), active strength [scaled from 0 to 5] and m. rectus femoris spasticity [MAS] for the walking classification types 0 to 4 (T0-T4) of USCP patients, total USCP sample and typically developing controls (TD); pathologic limb was considered for USCP, prime limb for TD.

parameter	USCP walking types					USCP total (n = 64)	TD (n = 30)
	T4 (n = 11)	T3 (n = 18)	T2 (n = 13)	T1 (n = 12)	T0 (n = 10)		
age [years]	11.7(3.3)	8.7(2.6)	9.4(3.2)	9.4(3.2)	8.7(2.8)	9.5 (3.0)	9.7(2.7)
body height [cm]	146.0(17.8)	133.0(15.4)	138.0(18.1)	141.0(18.1)	136.0(14.2)	138(17.2)	143.0(17.9)
bodyweight [kg]	35.2(10.9)	31.1(10.9)	34.7(16.1)	36.4(16.1)	32.4(9.0)	33.7(12.4)	35.2(12.7)
leg length difference [cm]	−1.3(0.8)	−1.0(1.0)	−1.0(0.5)	−1.1(0.5)	−1.1(1.3)	−1.1(0.9)	0.1(0.6)
non-dim. velocity	0.37(0.05)	0.44(0.05)	0.45(0.06)	0.45(0.06)	0.49(0.06)	0.44(0.06)	0.48(0.05)
non-dim. step length	62.2(4.2)	72.2(7.2)	74.1(9.1)	75.1(9.1)	77.3(7.6)	72.2(8.5)	82.1(6.8)
non-dim. step time	1.93(0.23)	1.84(0.18)	1.77(0.13)	1.84(0.13)	1.74(0.14)	1.83(0.17)	1.69(0.10)
Passive joint excursion[°]							
hip extension	−1.0(5.2)	−1.6(7.7)	0.5(11.3)	3.6(11.3)	2.0(9.2)	0.5(8.9)	11.0(6.8)
knee extension	−2.9(4.7)	0.0(7.5)	4.6(6.9)	4.2(6.9)	0.0(4.1)	1.3(6.4)	4.8(4.3)
popliteal angle	25.9(9.4)	27.0(14.2)	24.0(21.1)	22.5(21.1)	24.4(27.6)	25.0(17.6)	8.0(11.2)
ankle dorsiflexion	3.2(8.2)	−0.3(8.7)	−3.6(4.5)	2.5(4.5)	7.0(7.5)	1.5(7.7)	15.4(5.9)
Active strength [0-5]							
hip flexion	4.3(0.8)	3.8(0.8)	4.1(0.5)	4.4(0.5)	4.8(0.5)	4.2(0.7)	4.9(0.4)
hip extension	3.5(1.3)	3.8(1.0)	3.8(1.3)	4.2(1.3)	3.9(0.8)	3.8(1.1)	4.9(0.3)
knee flexion	3.8(0.8)	3.7(0.8)	4.1(0.6)	4.3(0.6)	4.4(0.5)	4.0(0.7)	4.9(0.5)
knee extension	4.1(0.7)	3.9(0.8)	4.5(0.4)	4.6(0.4)	4.7(0.4)	4.3(0.7)	5.0(0.0)
ankle dorsiflexion	2.7(1.6)	2.7(1.4)	2.5(1.5)	2.9(1.5)	3.0(1.1)	2.8(1.3)	5.0(0.1)
ankle plantarflexion	2.4(1.3)	2.7(1.1)	2.9(1.6)	3.3(1.6)	3.6(0.6)	3.0(1.2)	5.0(0.0)
Spasticity [MAS]							
m. rectus femoris	1.27(1.35)	0.46(0.66)	0.27(0.47)	0.18(0.47)	0.30(0.48)	0.50(0.83)	0.00(0.00)

adaptation in the USCP patients' pathologic and contralateral limb. However, for both parameters the significant group × limb side effect indicates that the patients' contralateral limb showed higher values than the pathologic limb, which is also the case for the ankle DF stance parameter. The contralateral limbs' higher ankle dorsiflexion in stance and swing as well as higher hip excursion is a mechanism to reduce functional or anatomical leg-length discrepancy with a longer contralateral limb [9]. Considering the knee RoM parameter, the patients' contralateral limb showed a poor walk-run adaptation (< 3°), whereas the pathologic limb adapts similar to the TD group (15°). Because of that, the group × locomotion interaction and the group × locomotion × limb side interaction were significant, though the pathologic limb showed normal adaptation. The poor walk-run adaptation of the patients' contralateral knee excursion may relate to the sufficient compensation of the hip and the ankle joint so that an increase in knee RoM in the contralateral limb is not necessary to adapt to running. The significant interaction effects for the ankle DF stance parameter support the findings of the walk/run-classification that USCP patients show poor ankle dorsiflexion adaptation in stance phase during running. Contrary to our findings, Davids et al. [7] showed that diplegic CP patients have poor potential to adapt to running respective of knee RoM (patients deteriorated by 2° from walking to running) and peak DF (patients improved by only 1° from walking to running). However, Böhm et al. [10] showed curves of USCP and diplegic CP patients exhibiting sagittal gait curves that indicate that patients show considerable higher adaptation from walking to running than the patients in Davids' [7] findings.

Running is associated with higher locomotion velocity, increased generating and absorbing powers [7,8]. Therefore, higher muscular stretch velocities, higher spastic stretch reflexes, and thus aggravation of the walking abnormalities and inadequate adaptation to running would be expected. This was only observed for the ankle DF stance parameter in this study. For ankle DF in swing, knee, and hip RoM the flexor synergies of the hip and knee flexor and ankle dorsiflexor muscles may be activated with more normality during running and they may be less influenced by spasticity. Therefore, we suppose that cerebral control is less dominant during running. Perry et al. [11] described that the control of locomotion that generates extensor and flexor muscle activation can be evoked by two different mechanisms independent from cerebral control: stretch for the flexor pattern and joint posture for the extensors. Ivanenko et al. [12] described a higher activation of lumbosacral motor neurons when humans run. With increasing running velocity, the neuronal activation of the lower spinal cord increases. The motor neurons in the lumbosacral area are responsible for controlling the lower limb muscle activation and associated as central pattern generators (CPG) area. The CPG are the locomotor network responsible for timing and phasing complex muscle activity. CPG are capable of generating rhythmic patterned output without sensory input [13]. Patients with acute vestibular disorder, e.g., are able to balance better when running than when standing or walking. In running, they can maintain direction and feel more secure, whereas in walking they fail to move without to brace. Healthy subjects who are manipulated by rotations on a chair also feel that it is easier to maintain balance afterwards during running compared to walking. It is assumed that automatic spinal programs that inhibit the descending vestibular sensory inflow would explain these observations. Once a highly automatic locomotor pattern has been initiated, this may suppresses vestibular and somatosensory input [14].

These findings from literature and the findings of this present study lead us to the assumption that the spinal locomotor control through CPG enhances during running while the cerebral influence seems to be relatively weaker. For CP patients this would imply that their functionally impaired cerebral structures are less dominant in running which leads to a more normal running pattern. We assume that the equinus abnormality did not improve because a large proportion of patients with equinus abnormality had fixed ankle joint contractures.

Our results indicate that when switching into another locomotor pattern walking abnormalities that may require surgical intervention can be dissolved. Including running analysis into the gait analysis procedure can reveal whether patients can normalize their gait abnormality during running. A patient with an apparently stiff knee gait can possibly produce a running pattern closer to normal without showing knee dysfunction (Fig.1A). The treatment recommendations described by Rodda et al. [4] are in practice partially applied methods, but do not strictly reconcile with classification types: Rectus femoris muscle transfer for knee joint contracture treatment or iliopsoas muscle

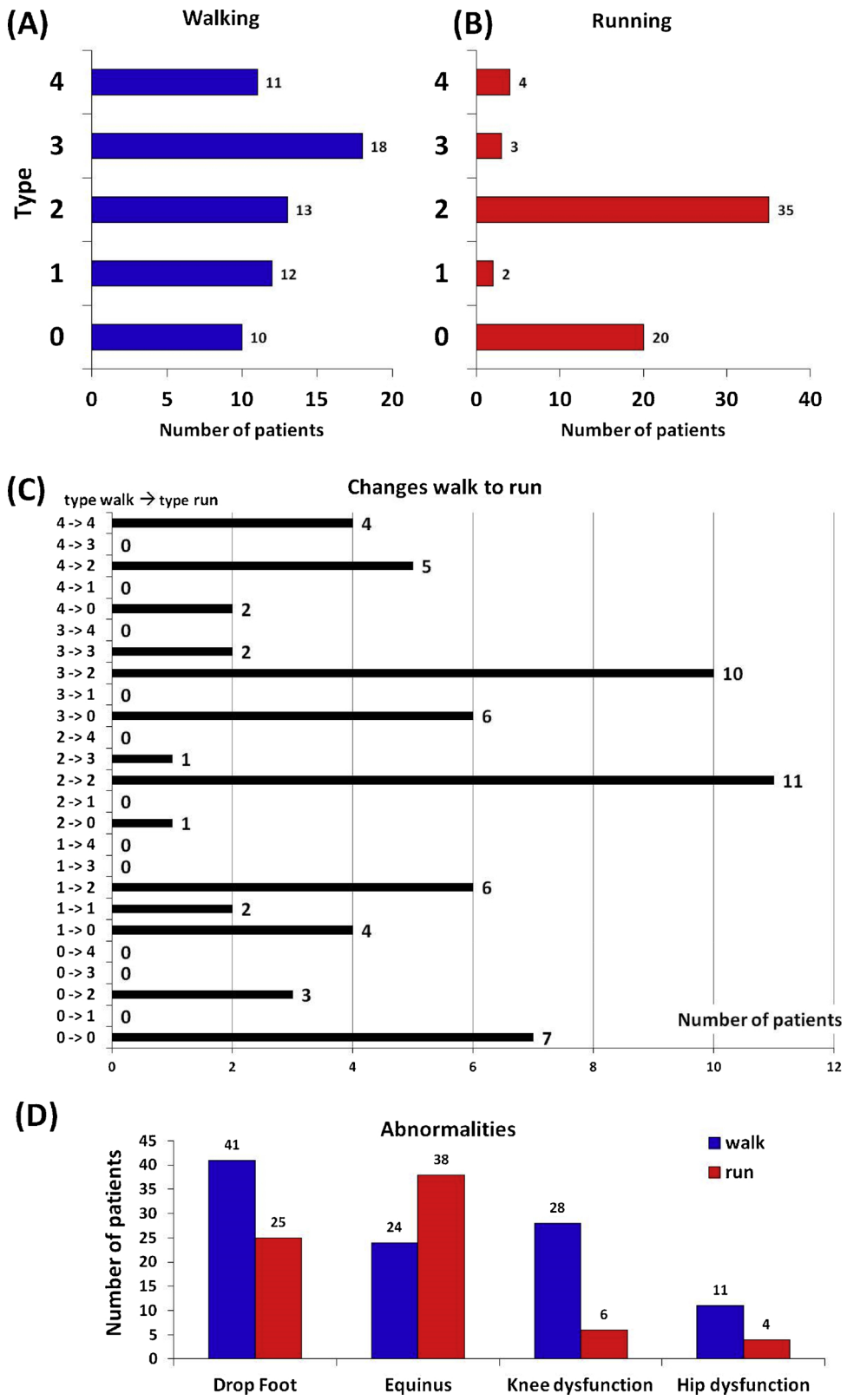

Fig. 2. A: Number of patients with types 0, 1, 2, 3 or 4 in walking; B: Number of patients with types 0, 1, 2, 3 or 4 in running; C: Number of patients' changes of classification type from walking to running. D: Number of patients with occurring abnormalities drop foot, equinus, knee dysfunction and hip dysfunction.

lengthening for hip joint contracture treatment was not performed in any of our patients. Therefore, we cannot evaluate whether it may have helped to improve stiff knee gait during walking. The most common surgical treatment in the USCP patients of this study were calf muscle lengthening procedures performed in 52% of the patients with equinus abnormality. Also 83% of those patients were treated with an ankle foot orthosis. Thus the equinus deformity is the most relevant abnormality to treat. In practice, functional problems, pain and preventative issues determine further treatment procedures rather than classification types.

We suggest that further research should investigate the influence of

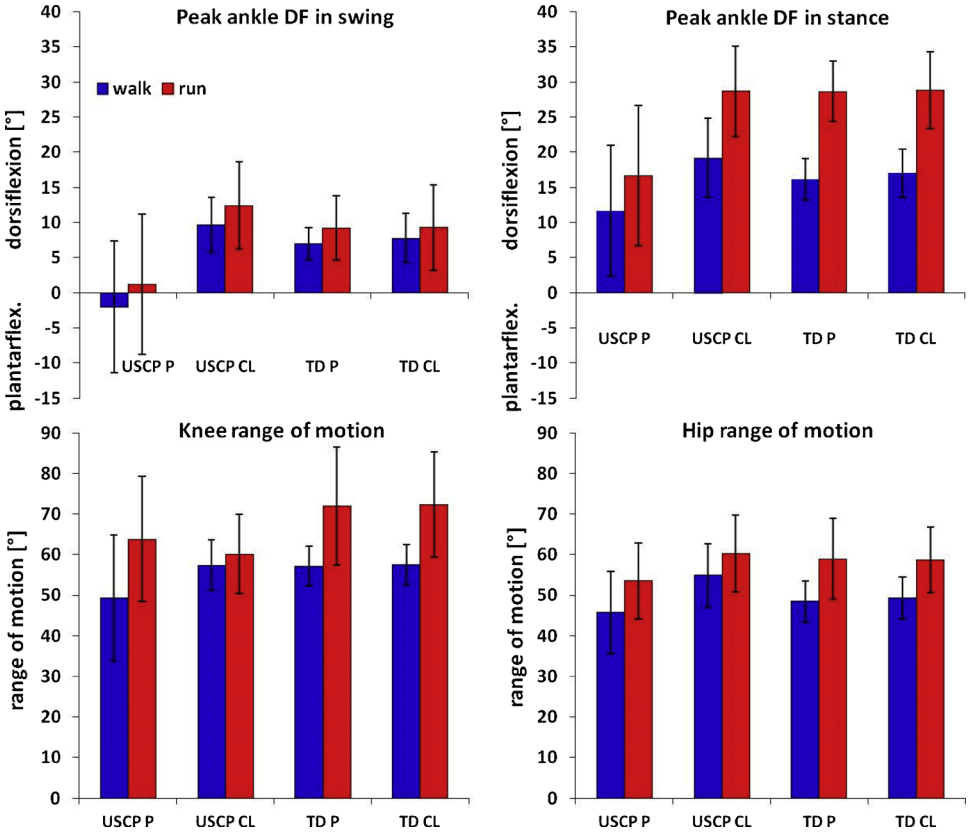

Fig. 3. Mean values with SD of peak ankle DF swing, peak ankle DF stance, knee RoM and hip RoM in degree [°]; blue bars for walk, red bars for run; USCP P: pathologic limb of USCP participants; USCP CL: contralateral limb of USCP participants; TD P: prime limb of TD participants; TD CL: contralateral limb of TD participants (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

CPG-associated regions and cerebral influences in running compared to walking. This could be assessed through transcranial magnetic stimulation (TMS) experiments during walking and running. With TMS-stimulation/inhibition of the motor cortex the influence and proportion of cerebral structures compared to spinal areas could possibly be evaluated. TMS studies could alternatively investigate whether different neural structures within the brain associated with locomotion alternate their influence and contribution during running compared to walking.

Since lumbosacral motor neuron activation and associated CPG activation increases with increasing walking velocity and running [12], one could additionally investigate whether running or fast walking exercises can possibly be advantageous for walking performance of patients. In exercises where cerebral influence is assumed to be less dominant, the spastic muscles may have a more normal metabolic adaptation and thus a better ability to train their aerobic endurance. Furthermore a better strengthening of those muscles may be possible, especially when training at higher intensities (e.g. sprinting exercises). Therefore, these exercises could facilitate patients' everyday lives, because higher aerobic capacity and muscle strength is related to a higher participation level and increased quality of life [15].

Because the Plug-in-Gait-model does not divide the foot into segments, contortion between the hindfoot and forefoot or a midfoot break cannot be detected. As a result, the Plug-in-Gait model may overestimate the actual dorsiflexion of a patient with a midfoot break [16]. A more detailed foot model may be more accurate. Furthermore, patients and TD all walked and ran barefoot during the gait analysis, which may not be appropriate reproductions of their everyday walking and running style. Thus, TD as well as patients without equinus abnormality often used a forefoot running style to prevent possible uncomfortable feedback from the hard walkway and reduce collision forces triggered by a barefoot heel strike [17].

5. Conclusion

As the first study to compare sagittal walking and running patterns in USCP to TD including both limbs, the findings from this study imply that there is a natural ability for USCP patients to exceed their walking values comparable to TD by switching into the running pattern. In running, three of four typically sagittal plane abnormalities in USCP children normalized and the respective parameters showed normal

Table 2
P-values and effect sizes (partial eta-square, η^2) of main effects and interaction effects from three-factor ANOVA for factors group (gr: USCP/TD), locomotion (loc: walk/run) and limb side (side: pathologic or prime/contralateral); * significant at $p \leq 0.05$ level.

Effects	Factors	Ankle DF swing		Ankle DF stance		Knee RoM		Hip RoM	
		p	η^2	*p*	η^2	*p*	η^2	*p*	η^2
Main effects	gr	0.010*	0.07	0.003*	0.09	< 0.001*	0.13	0.858	< 0.01
	loc	< 0.001*	0.24	< 0.001*	0.82	< 0.001*	0.60	< 0.001*	0.55
	side	< 0.001*	0.37	< 0.001*	0.29	0.330	0.18	< 0.001*	0.01
Interaction effects	gr × loc	0.239	0.02	< 0.001*	0.22	0.003*	0.09	0.034*	0.05
	gr × side	< 0.001*	0.33	< 0.001*	0.25	0.470	0.01	< 0.001*	0.16
	loc × side	0.397	0.01	0.011*	0.07	< 0.001*	0.14	0.014*	0.06
	gr × loc × side	0.802	0.01	0.001*	0.11	< 0.001*	0.14	0.375	0.01

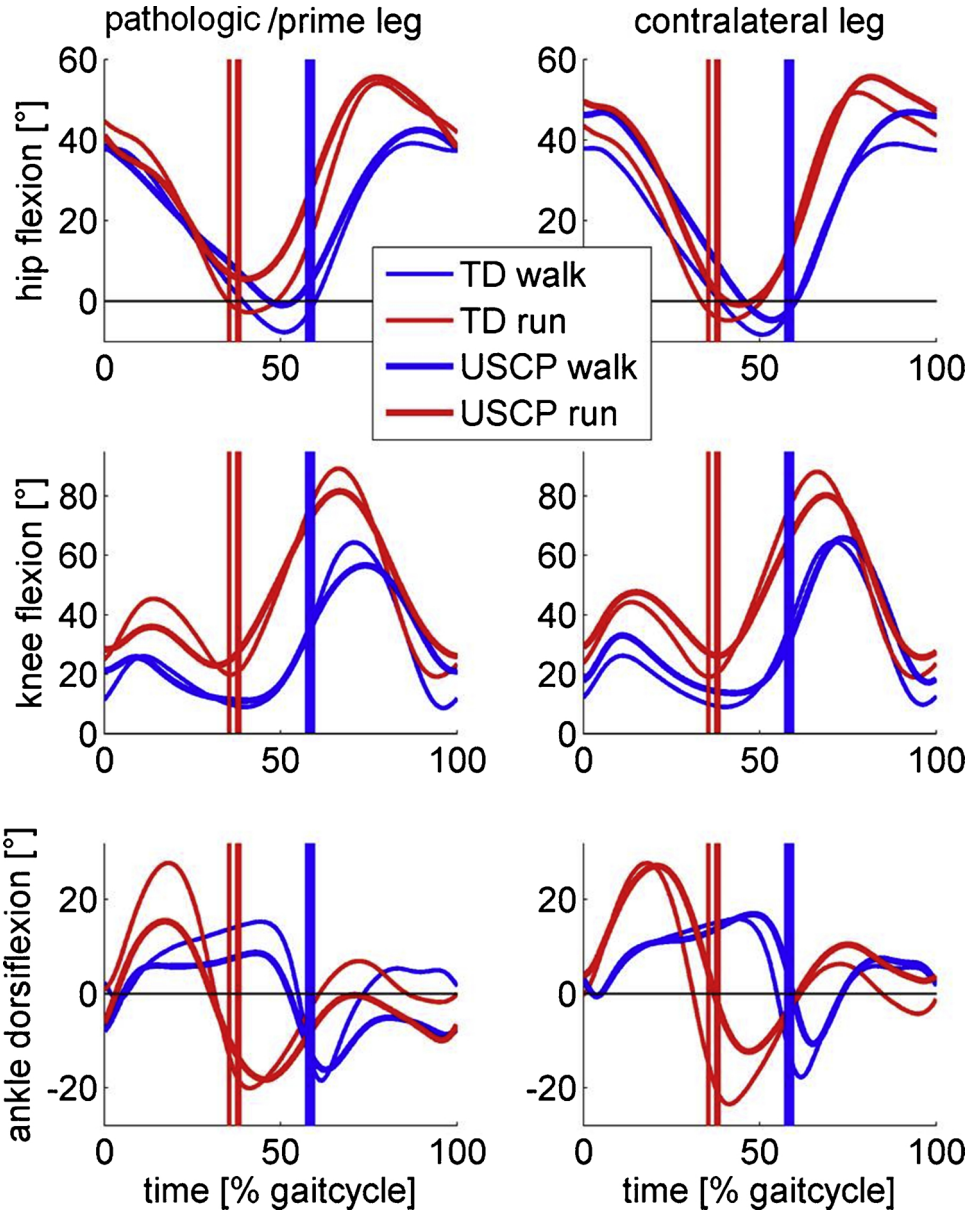

Fig. 4. Sagittal kinematics of USCP (thick curves) and TD (thin curves) of pathologic/prime and contralateral leg in running (red curves) and walking (blue curves) for hip flexion, knee flexion and ankle dorsiflexion in degree [°]; vertical lines indicate toe-off moment (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

adaptation of the pathologic limb similar to the TD sample. Running revealed that the equinus abnormality is the main problem for USCP patients. For treatment decision making we suggest including a running analysis if possible.

The influence of the neuronal locomotion networks in the spinal cord compared to cerebral control could be more dominant during running. Therefore, further research should focus on the neuronal mechanisms underlying walking and running with regards to patients' necessity for surgical treatment and possible alternative non-surgical treatments.

Conflict of interest statement

All authors do not have any financial and personal relationships with other people or organizations that inappropriately influence the work performed.

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